Optics Measurements at the Tevatron

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Abstract

This talk gives a summary of accomplishments in measurement of the Tevatron optics parameters. The goal of the project was to build an accurate model of the machine which would ease future optics corrections and modifications. The method is based on the orbit response measurement and fitting. We present results of application of the technique and comparison with other methods.

Contents

- Computer model
- Differential orbit method
- Orbit response matrix fit
- Results of fitting, verification
- Summary

Computer Model

- The model starts from power supply currents taken directly from the control system
- Parameters of magnets:
  - Dipoles have equal calibration and edge focusing; A1 (skew quad) component is individual in each magnet
  - All main lattice quadrupoles have calibration constants measured at the time of manufacturing
  - Trim quadrupoles and nonlinear elements have parameters equal within a family
  - Unknown quadrupole errors (to be found by measurements) are added to main quadrupoles. Include normal and skew components.
- We use OptiM accelerator optics code (V.Lebedev). The code implements fully coupled 4D parametrization.

Differential Orbit Measurements

- The aim is to find gradient errors utilizing the fact that quadrupoles act as dipole correctors with off-center orbit

$$\theta = Kl \cdot x$$

- Initially, closed orbit is excited using a single dipole corrector

$$x_i(s) = \frac{\sqrt{\beta(s)}}{2\sin(\pi\nu)}\theta\sqrt{\beta(s_0)}\cos\left(\left|\varphi(s)-\varphi(s_0)\right|-\pi\nu\right)$$

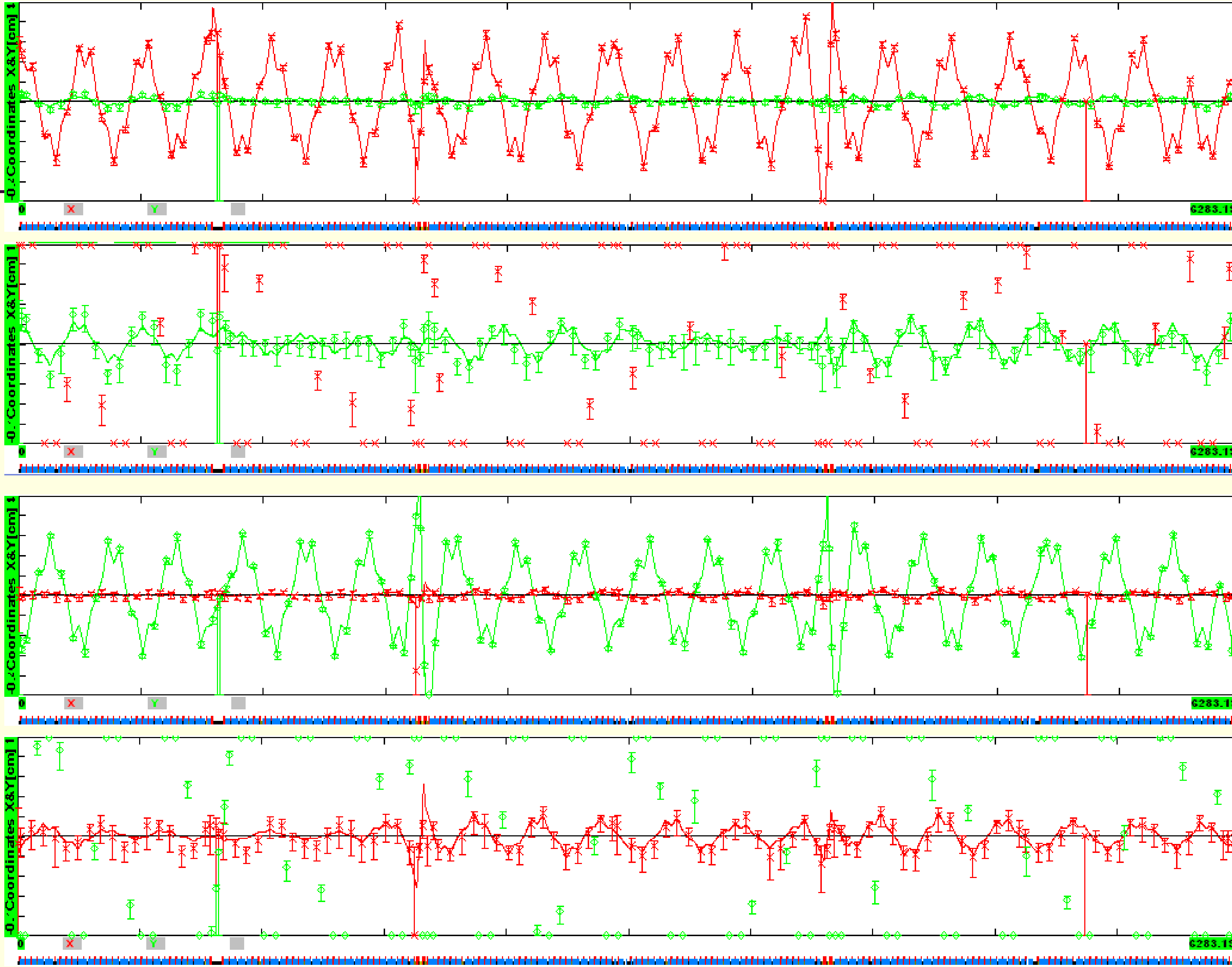
- The orbit distortion due to quadrupoles is given by

$$x_q(s) = \frac{\sqrt{\beta_x(s)}}{2\sin(\pi\nu_x)}\sum_j Kl_j x_{ij}\sqrt{\beta_{xj}}\cos\left(\left|\varphi_x(s)-\varphi_{xj}\right|-\pi\nu_x\right)$$

$$y_q(s) = \frac{\sqrt{\beta_y(s)}}{2\sin(\pi\nu_y)}\sum_j SQ_j x_{ij}\sqrt{\beta_{yj}}\cos\left(\left|\varphi_y(s)-\varphi_{yj}\right|-\pi\nu_y\right)$$

- Dispersion measurement $x_d(s) = -\dfrac{D(s)}{\eta}\dfrac{\Delta f_{RF}}{f_{RF}}$

- Use BPM system to measure and record orbit differences


Coordinates X&Y[cm]
0
X
Y
6283.19

Orbit Response Matrix Fit (LOCO, V.Sajaev, ANL)

The orbit response matrix is the change in the orbit at the BPMs as a function of changes in steering magnets:

$$\begin{pmatrix} x \\ y \end{pmatrix} = M_{\substack{measured \\ model}} \begin{pmatrix} \theta_x \\ \theta_y \end{pmatrix},$$

The main idea of the analysis is to adjust all the variables that the response matrix depends on in order to solve the following equation:

$$M_{measured} - M_{model}(z) = 0$$

$$\Delta z = \left(\frac{\partial M_{model}}{\partial z} \right)^{-1} \cdot \left(M_{measured} - M_{model}(z_0) \right)$$

Parameters of the Orbit Response Matrix

- Quadrupole gradient errors
- Steering magnet calibrations
- BPM gains
- Quadrupole tilts
- Steering magnet tilts
- BPM tilts
- Energy shift associated with steering magnet changes

Main parameters

Main coupling parameters

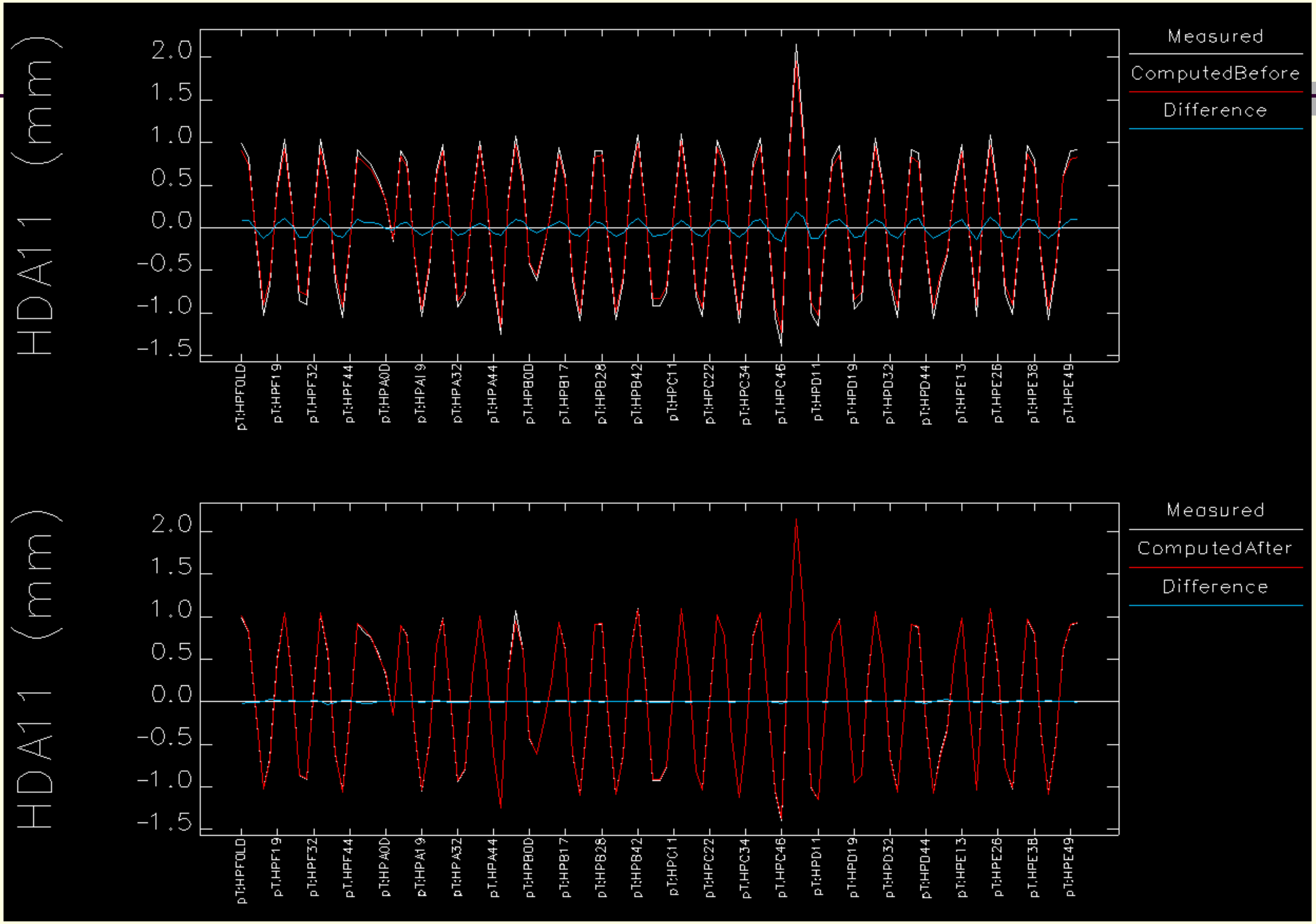
Parameters of the Tevatron

- 110 dipole correctors, 225 quadrupoles
- 118 BPMs in each plane, accuracy is ~10 μm, time of single measurement ~2 s

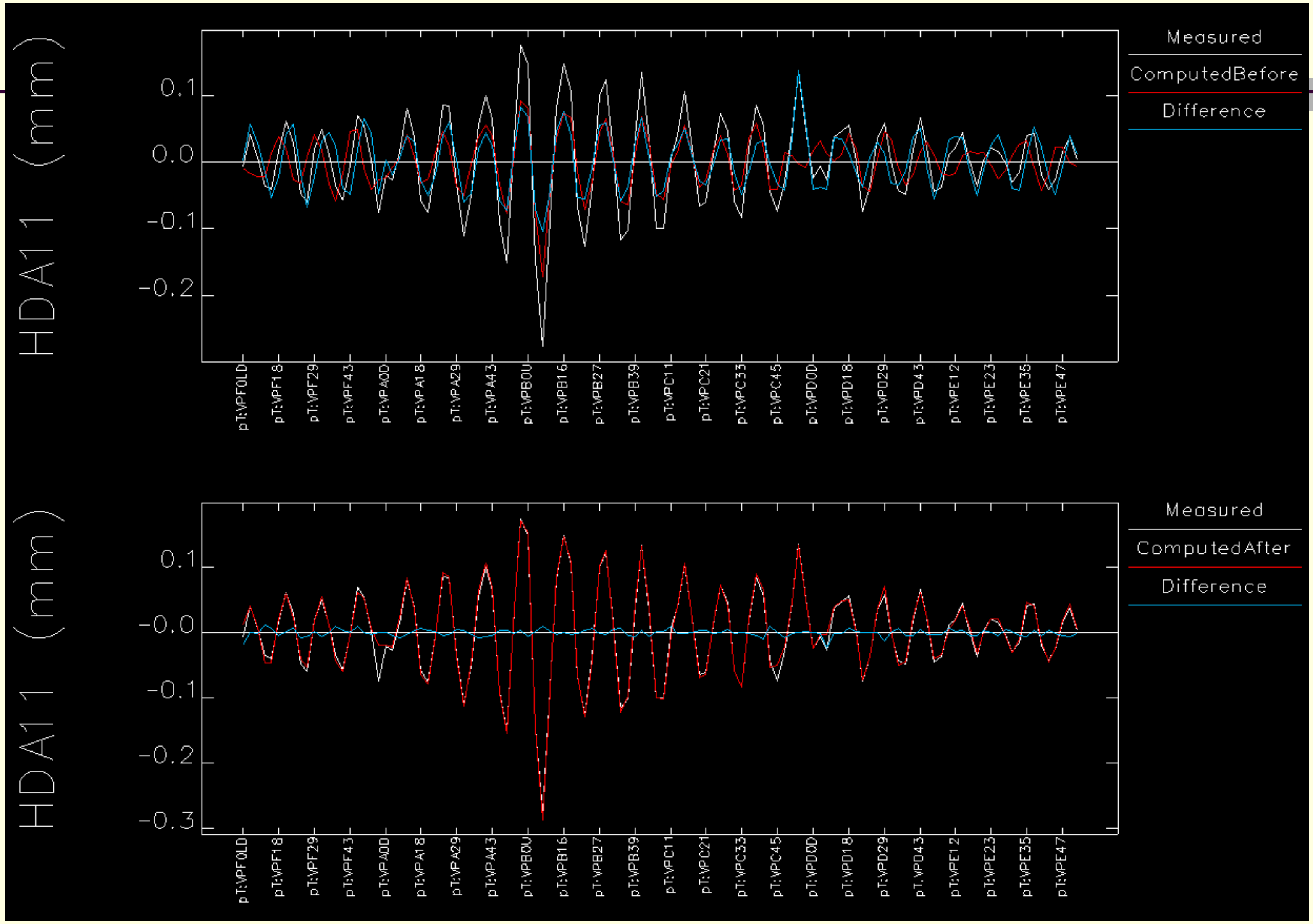
- With averaging over 20 measurements the data acquisition for half of the correctors takes ~1 hour
- For our analysis we use about half of steering magnets, all BPMs, all quadrupoles, and tilts of 1/2 of quadrupoles. The resulting number of variables is 980 and the response matrix has about 16,500x980 elements.
- Finally we solve the following equation (by iterations):

$$X = M^{-1} \cdot V$$

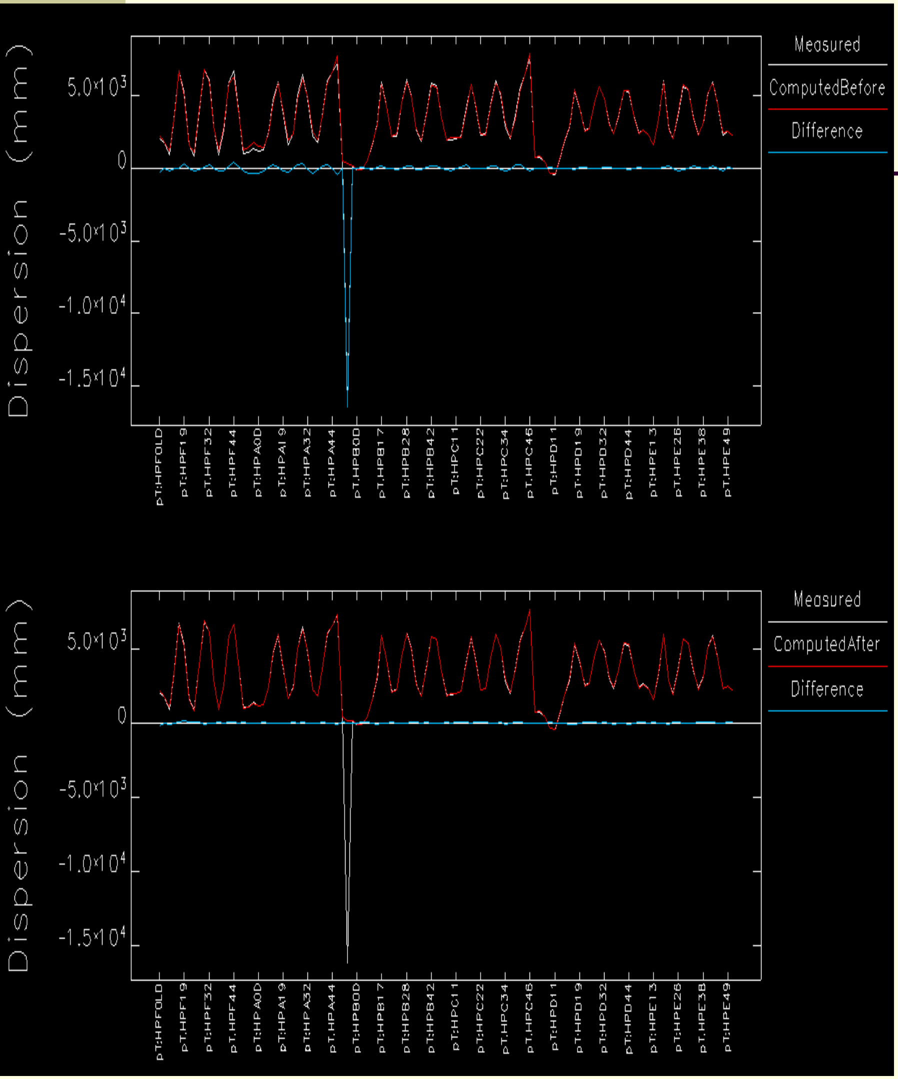
Differential Orbit. X Corr. – X plane

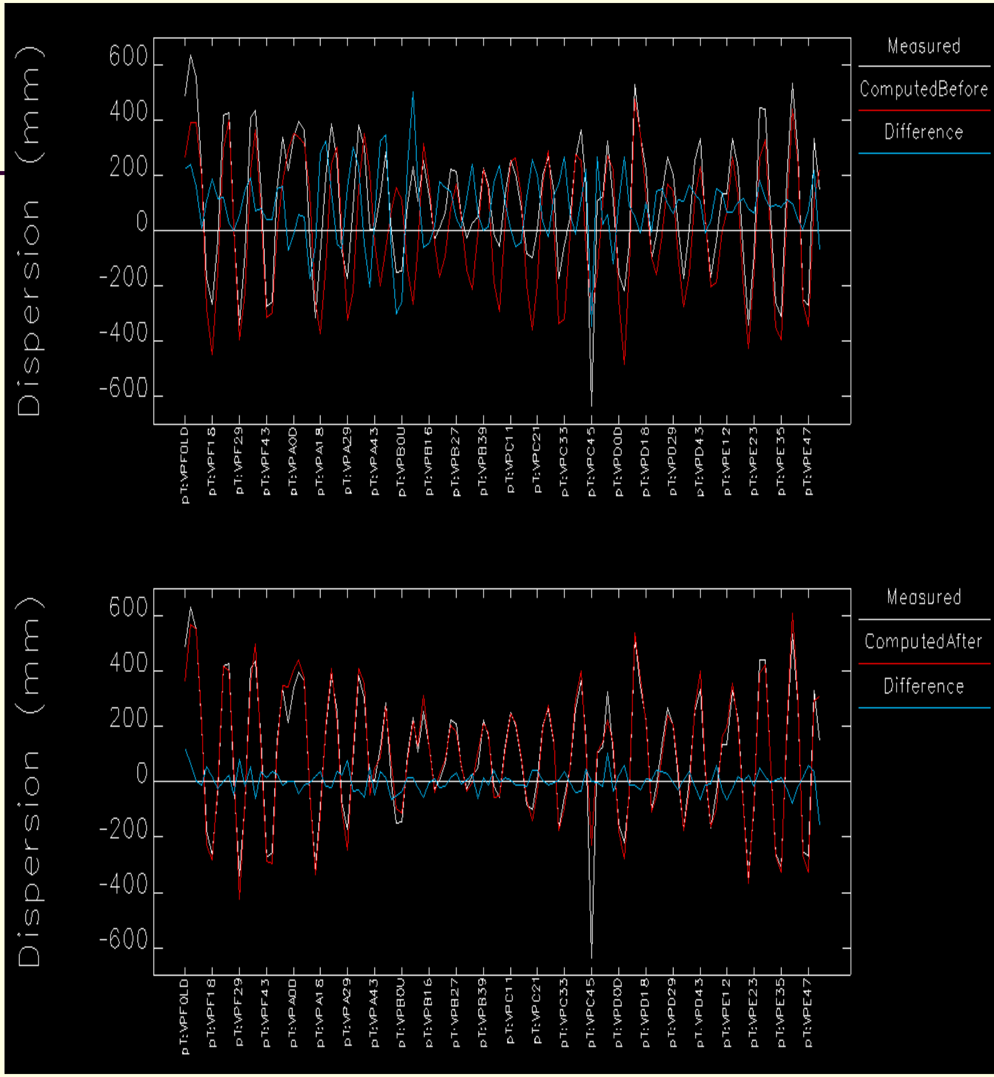


Differential Orbit. X Corr. – Y plane

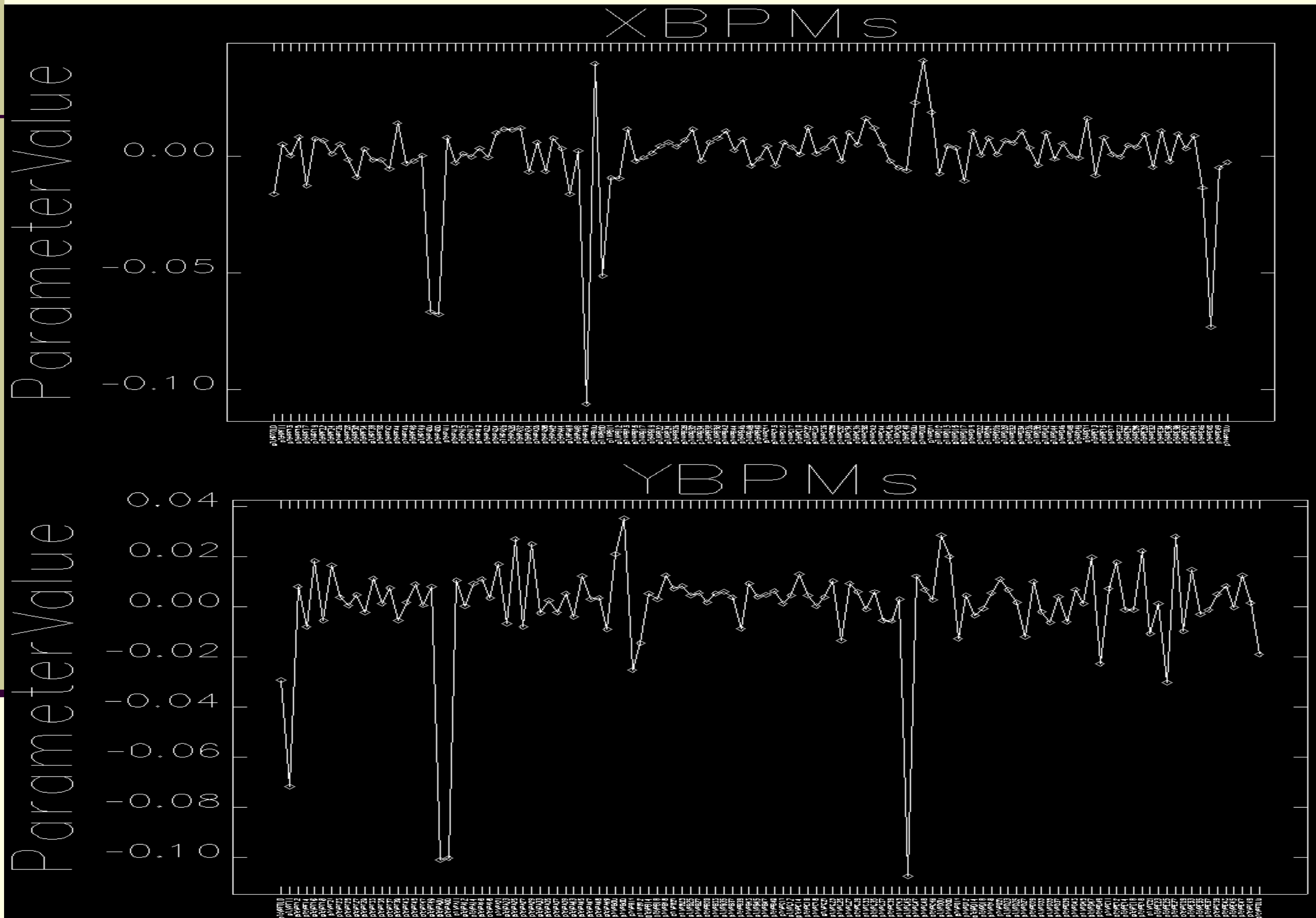


Dispersion

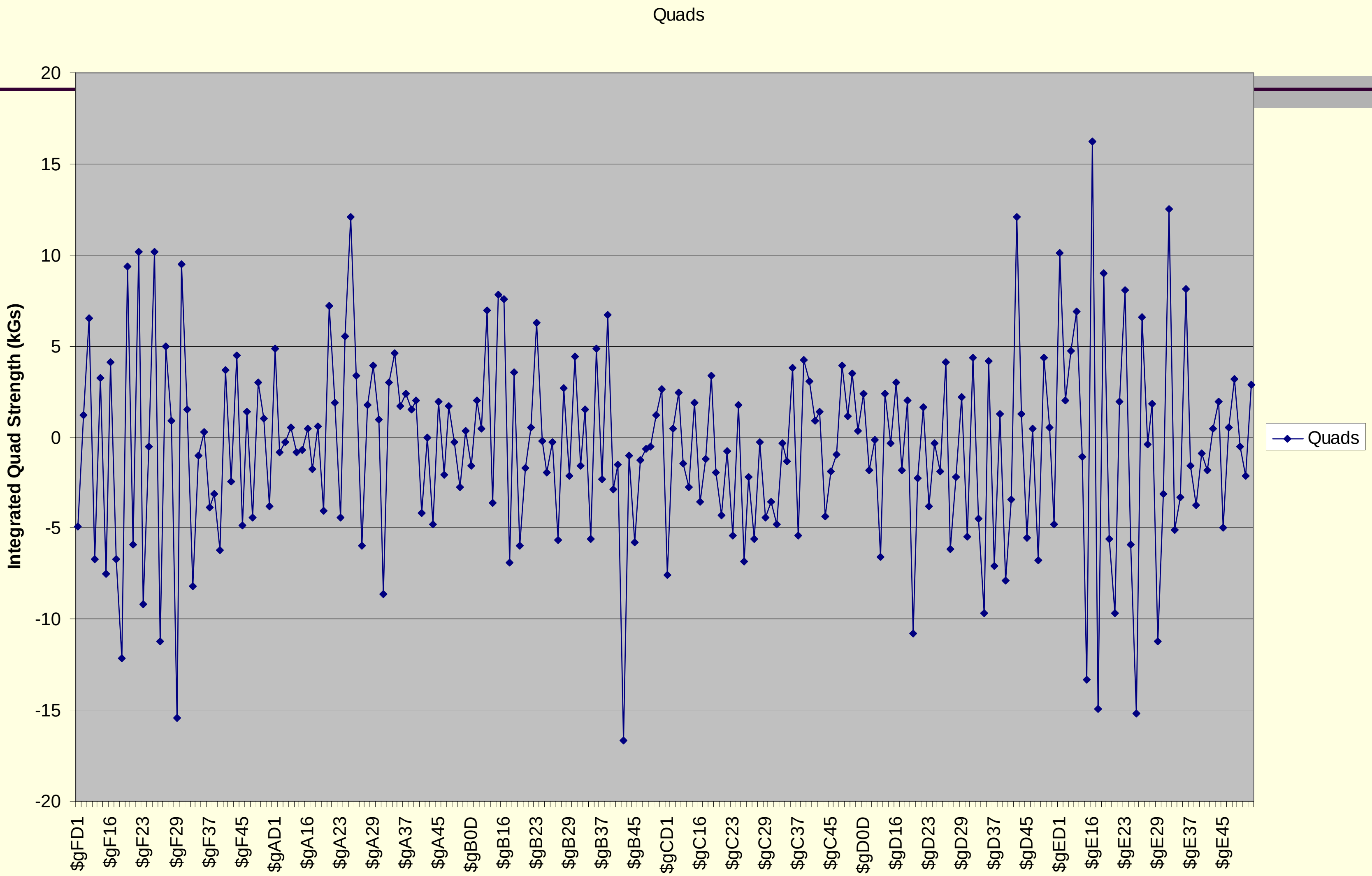

Dispersion (mm)
5.0×10³
0
-5.0×10³
-1.0×10⁴
-1.5×10⁴
Measured
ComputedBefore
Difference
Dispersion (mm)
5.0×10³
0
-5.0×10³
-1.0×10⁴
-1.5×10⁴
Measured
ComputedAfter
Difference
pT:HPF0LD pT:HPF19 pT:HPF32 pT:HPF44 pT:HPA0D pT:HPA19 pT:HPA32 pT:HPA44 pT:HPB0D pT:HPB17 pT:HPB28 pT:HPB42 pT:HPC11 pT:HPC22 pT:HPC34 pT:HPC46 pT:HPD11 pT:HPD19 pT:HPD32 pT:HPD44 pT:HPE13 pT:HPE26 pT:HPE38 pT:HPE49


Dispersion (mm)
600
400
200
0
-200
-400
-600
Measured
ComputedBefore
Difference
Dispersion (mm)
600
400
200
0
-200
-400
-600
Measured
ComputedAfter
Difference
pT:VPF0LD pT:VPF18 pT:VPF29 pT:VPF43 pT:VPA0D pT:VPA18 pT:VPA29 pT:VPA43 pT:VPB0U pT:VPB16 pT:VPB27 pT:VPB39 pT:VPC11 pT:VPC21 pT:VPC33 pT:VPC45 pT:VPD0D pT:VPD18 pT:VPD29 pT:VPD43 pT:VPE12 pT:VPE23 pT:VPE35 pT:VPE47

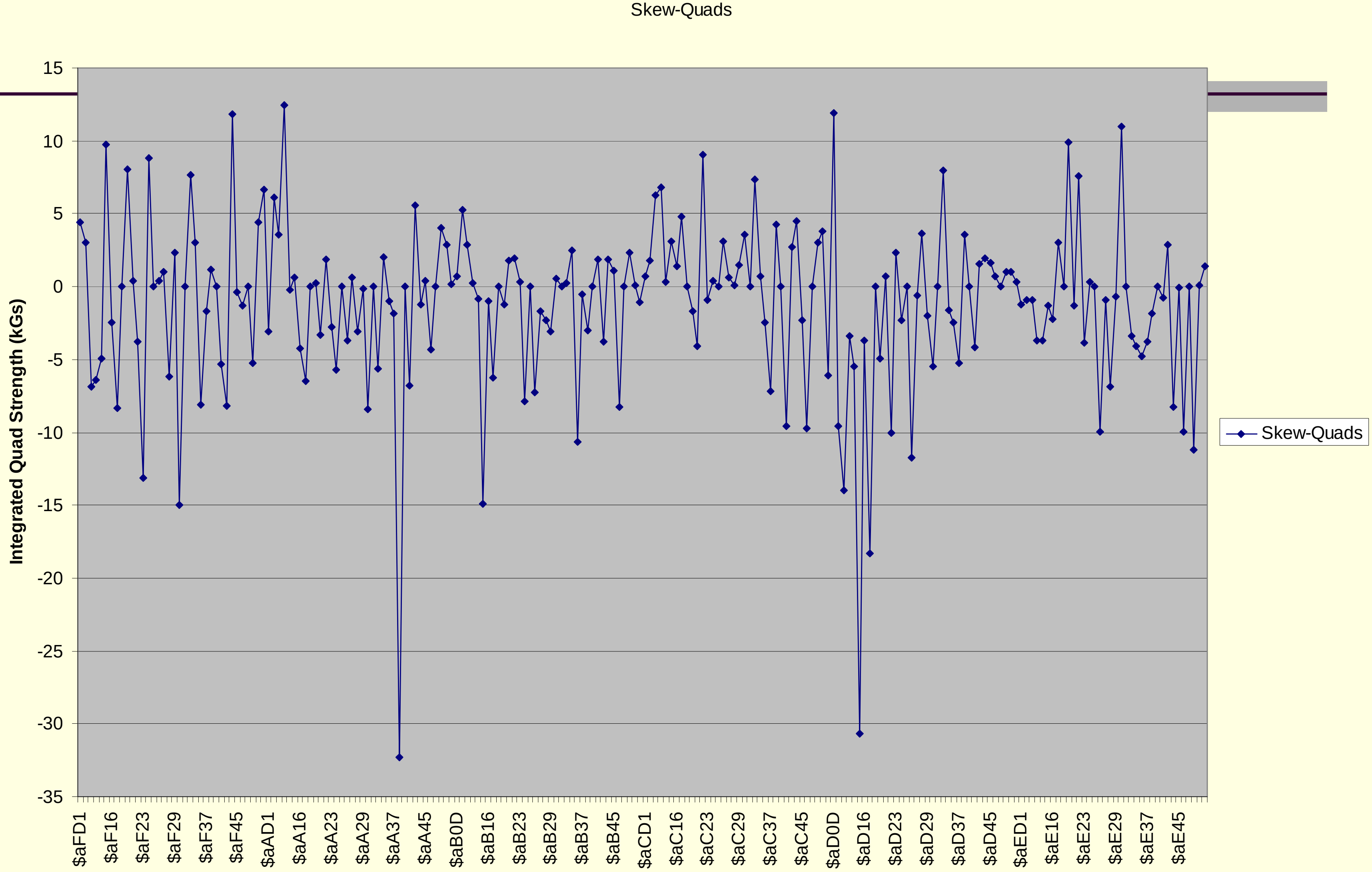
BPM Gains


XBPMs
Parameter Value
0.00
-0.05
-0.10
YBPMs
Parameter Value
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10

Fitted Quadrupole Errors



Fitted Skew-Quadrupole Errors

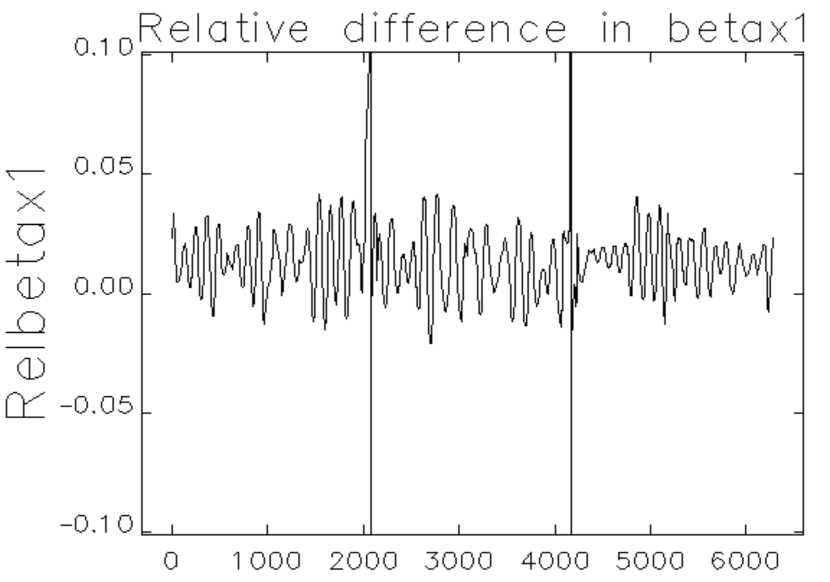


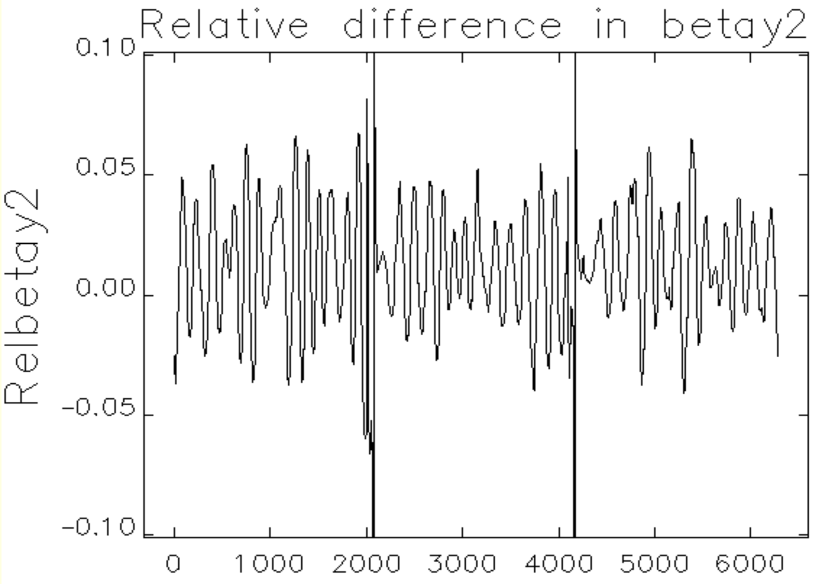
Summary of the Residual rms Errors After the Fit:

	x-x (μm)	y-x (μm)	x-y (μm)	y-y (μm)	h disp (mm)	v disp (mm)
Before	140	42	44	123	139	120
Set 1	13	8	11	9	50	39
Set 2	14	8	9	9	49	36

Beta Function Accuracy

- Beta functions are computed based on each set of variables, then average beta functions are calculated
- Difference between the average beta function and one of data sets:





- BetaX1 rms error – 2.2%
- BetaY2 rms error – 3.1%
- DispX rms error – 2.9%

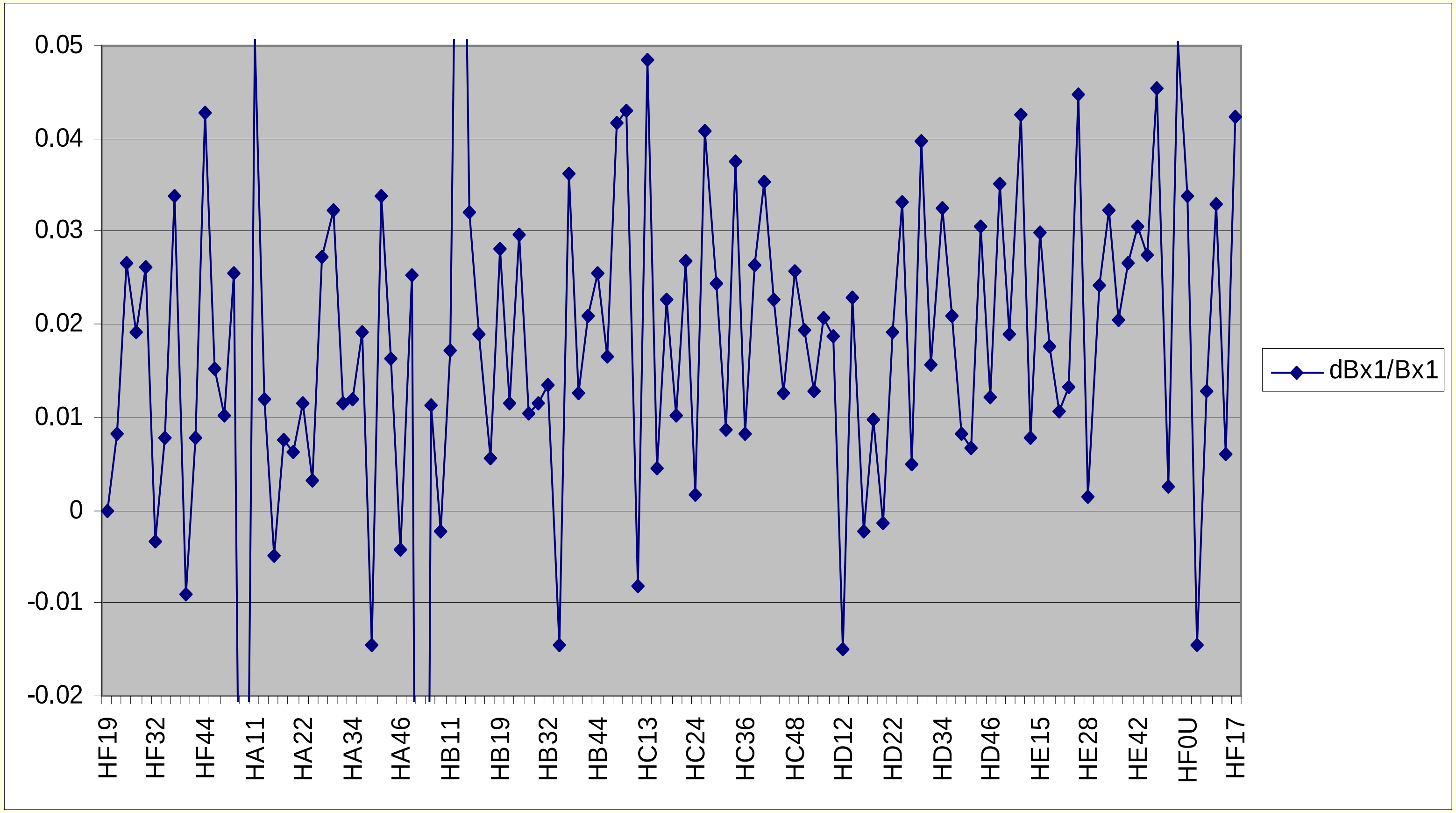
Measured and Computed Tuneshifts

Element	dQx Meas.	dQx Model.	Difference %			dQy Meas.	dQy Model.	Difference %		
T:QE17H	0.071	0.0072	**-1.7**	±	3	-0.002	-0.00177	**13**	±	11
T:QE19H	0.0050	0.0058	**-13**	±	3	-0.00194	-0.0025	**-23**	±	8
T:QE26H	0.0063	0.0064	**-2**	±	3	-0.002	-0.0021	**-4**	±	9
T:QE28H	0.0077	0.0076	**1.3**	±	3	-0.0018	-0.0016	**10**	±	12
T:QF28H	0.0058	0.0057	**2.2**	±	3	-0.0024	-0.0025	**-3.5**	±	8
T:QF32H	0.0078	0.0079	**-1.4**	±	3	-0.00205	-0.0017	**21**	±	12
T:QE47H	0.0027	0.00255	**6**	±	8	-0.0056	-0.0059	**-5.6**	±	3
T:QF33H	0.00245	0.00256	**-4.4**	±	8	-0.0069	-0.0067	**3.2**	±	3

- Vary current in quadrupoles which have separate power supplies and measure corresponding betatron tune shift

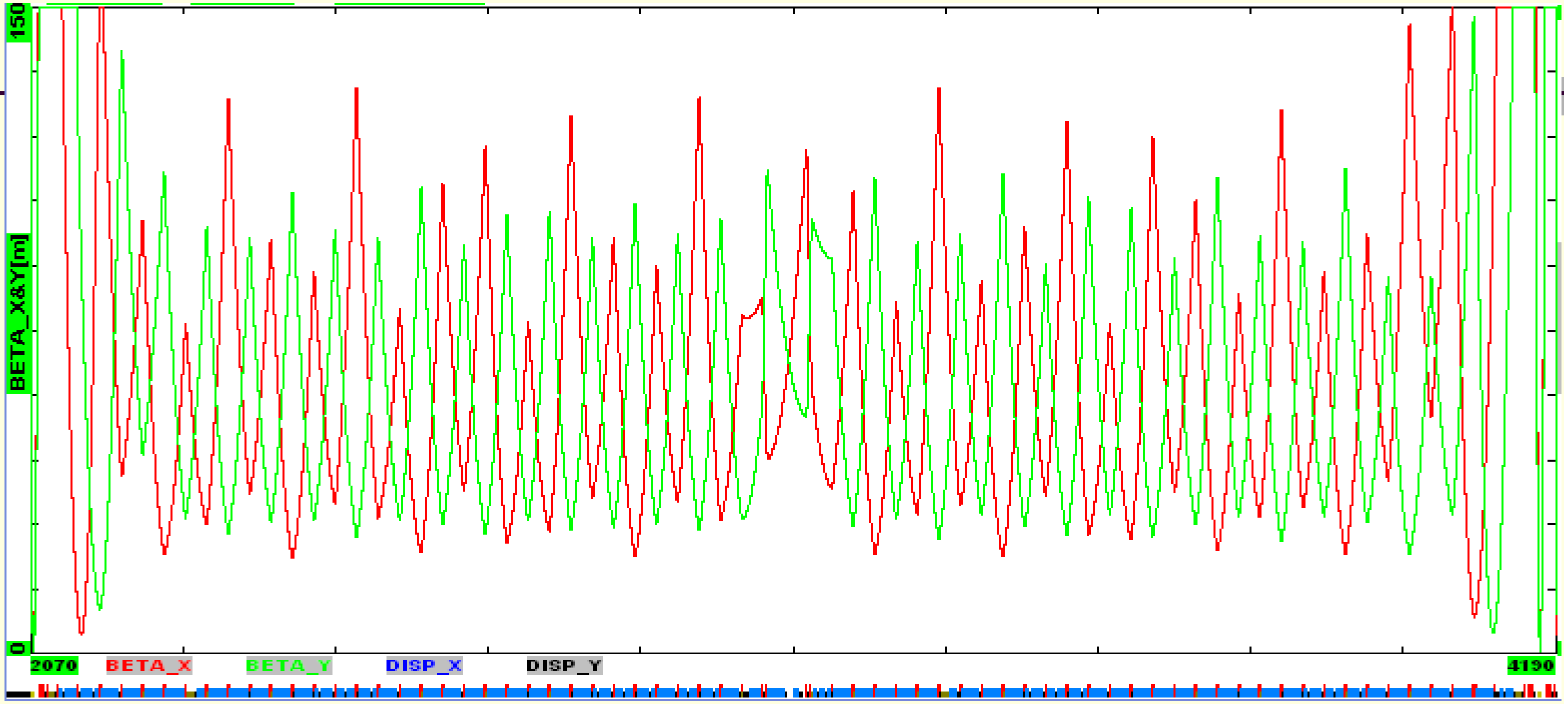
$$\Delta \nu = \frac{\Delta K \beta}{4\pi}$$

Comparison with Turn by Turn Method
(Yu. Alexahin, E. Gianfelice-Wendt)



Tevatron Beta Functions (short arc)

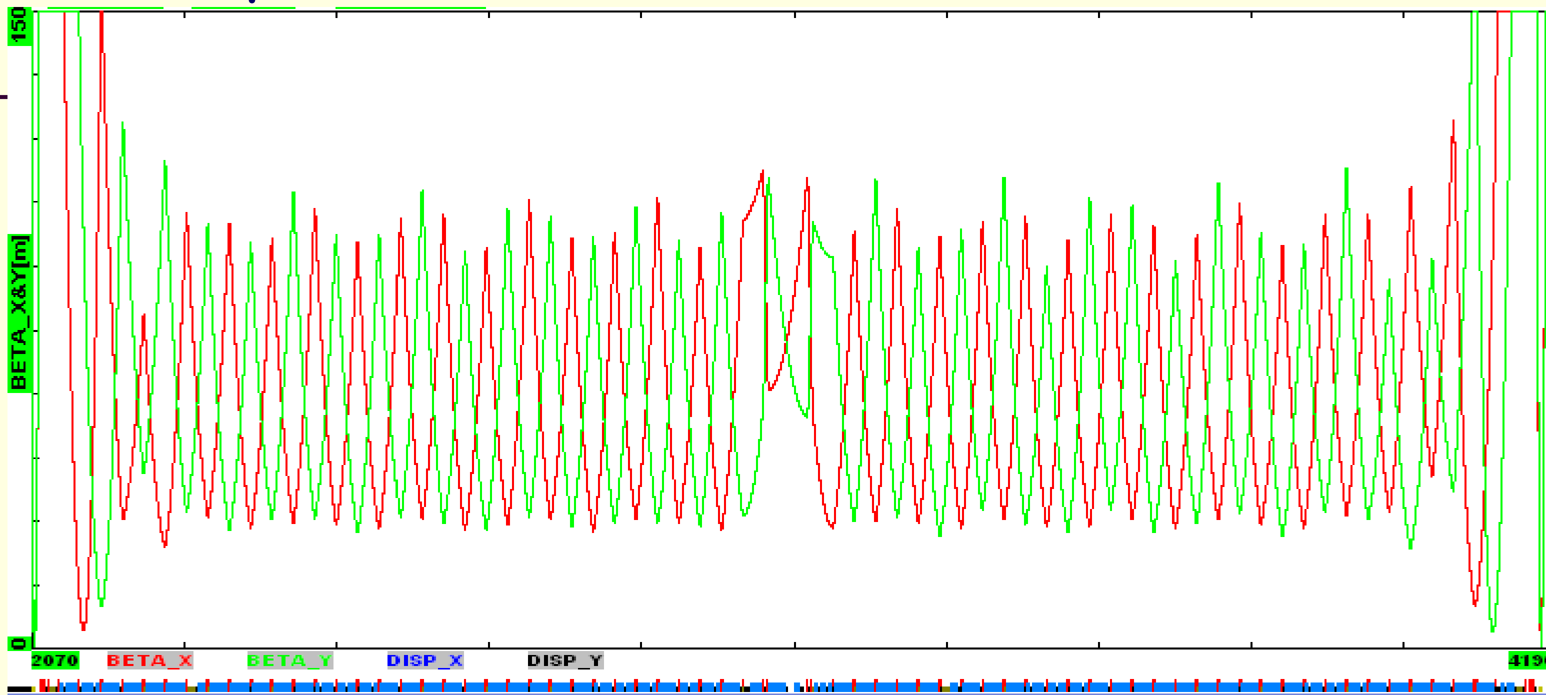
"35cm optics" before 9/21/05



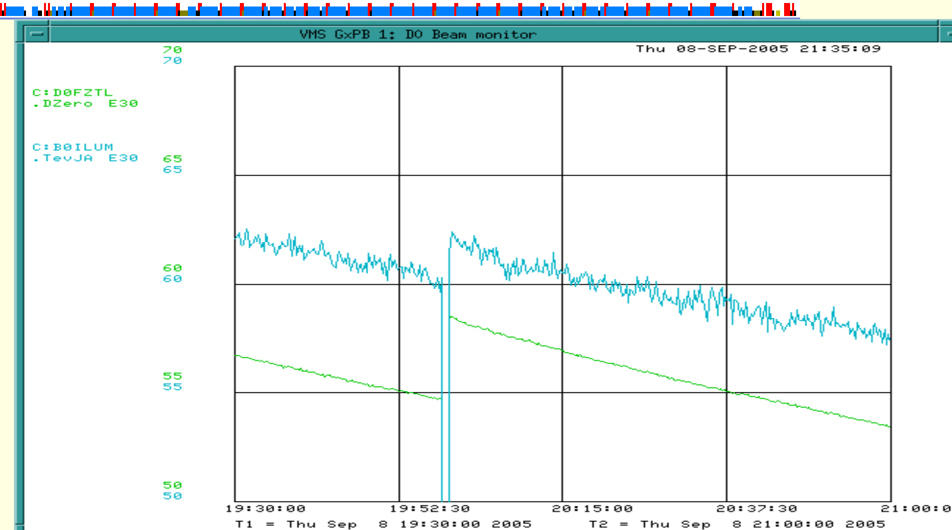
	β_x^* (cm)	β_y^* (cm)	
CDF	32.0	37.1	$\pm 5\%$
D0	35.8	40.0	$\pm 5\%$

Tevatron Beta Functions (short arc)

"28cm optics" after 9/21/05



	β_x^* (cm)	β_y^* (cm)
CDF	30.3	29.1
D0	29.2	28.2



Conclusion 1

- The response matrix fit method allows to pinpoint gradient errors in the Tevatron of the order of 2E-3. The error in beta function measurement is ~ 5%
- Measurements are in good agreement with results obtained by turn-by-turn and tuneshift methods
- Single measurement requires ~ 1 hour of the machine time. Data analysis takes ~ 6 hours.

Conclusion 2

- Based on the fitted model the optics modification has been done in order to:
  - Correct beta-beating in the arcs
  - Eliminate the difference between the two IPs
  - Decrease the beta* from 35 to 28 cm
- Peak luminosity of the collider with the new optics increased by 10%
- Further improvements are required to achieve better prediction accuracy, e.g. determination of parameters of individual trim elements